BGAs for High Reliability Applications

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WHY BGA

Ball Grid Array (BGA) is an important technology for utilizing higher pin counts, without the attendant handling and processing problems of the peripheral leaded packages. They are also robust in processing because of their higher pitch (0.050 inch typical), better lead rigidity, and self-alignment characteristics during reflow processing.

BGAs' solder joints cannot be inspected and reworked using conventional methods and are not well characterized for multiple double sided assembly processing methods. In high reliability SMT assembly applications, e.g. space and defense, the ability to inspect the solder joints visually has been standard and has been a key factor in providing confidence in solder joint reliability.

Unlike commercial applications which measures reliability failures in parts per million, the acceptable risk for the success of a space mission is associated with the first failure of electronic parts or interconnection. In addition, every space mission is unique and the electronic boards are specially designed for specific missions. Space applications may range from shuttle missions lasting a few days to missions outer solar systems requiring multi-decade service life.

The difference in reliability requirements plays a key role in the selection/design and inspection/testing processes. Even though the highest reliability is demanded, it is extremely difficult to quantify the reliability level requirement and demonstrate its indices. One reason is due to the unavailability of solder joint field data and failure statistics. This limits the exact definition of reliability assurance. Assurance must depend on qualification testing methodologies unique to accelerated environments along with credible analytical prediction.

The current constraint on budgets and changes in military specifications along with the applications of bold new technologies for space missions necessitates the use of advanced commercial electronic packages. Use of advanced packages including BGAs and CSPs, specifically their plastic versions, are contingent upon resolution of many issues of space applications such as radiation damage and consideration for thermal/vacuum environment.

To understand and address many common quality and reliability issues of BGAs, JPL organized a consortium with sixteen members in early 1995[1]. Diverse membership including military, commercial, academia, and infrastructure sectors which permitted a concurrent engineering approach to resolving many challenging technical issues.

BGA TEST VEHICLE CONFIGURATION

The two test vehicle assembly types were plastic (PBGAs) and ceramic (CBGAs) packages. Both FR-4 and polyimide PWBs with six layers, 0.062 inch thick, were used.

Plastic packages covered the range from OMPAC (Overmolded Pad Array Carrier) to SuperBGAs (SBGAs). These were:
- Two peripheral SBGAs, 352 and 560 I/O
- Peripheral OMPAC 352 I/O, PBGA 352 and 256 I/O
- Depopulated full array PBGA 313 I/Os
- 256 QFP (Quad Flat Pack), 0.4 mm Pitch

In SBGA, the IC die is directly attached to an oversize copper plate providing better heat dissipation efficiency than standard PBGAs. The solder balls for plastic packages were eutectic (63Sn/37Pb).

Ceramic packages with 625 I/Os and 361 I/Os were also included in our evaluation. Ceramic solder balls (90Pb/10Sn) with 0.035 inch diameters had a high melting temperature. These balls were attached to the ceramic substrate with eutectic solder (63Sn/37Pb). At reflow, package side eutectic solder and the PWB side eutectic paste will be reflowed to provide the electro-mechanical interconnects.

Plastic packages had dummy and daisy chains with the daisy chains on the PWB designed to be able to monitor critical solder joint regions. Most packages had four daisy chain patterns, 560 I/O had five, and the QFP had one.

Package Dimensional Characteristics

Package dimensional characteristics are among the key variables that affect solder joint reliability. Dimensional characteristics of all packages were measured using a 3D laser scanning system for solder ball diameter, package warpage, and coplanarity[2]. Examples of ball coplanarity distributions for a CBGA 625 and a SBGA 560 are shown in Figures 1 and 2 respectively. For the CBGA, the ball heights were generally uniform in distribution with few at the two extreme levels that were randomly distributed. The SBGA, however, reveals a nonuniformity where one region shows higher heights than the other. Such nonuniformity could cause package lifting during reflow; thus, increasing susceptibility to manufacturing defect formation.

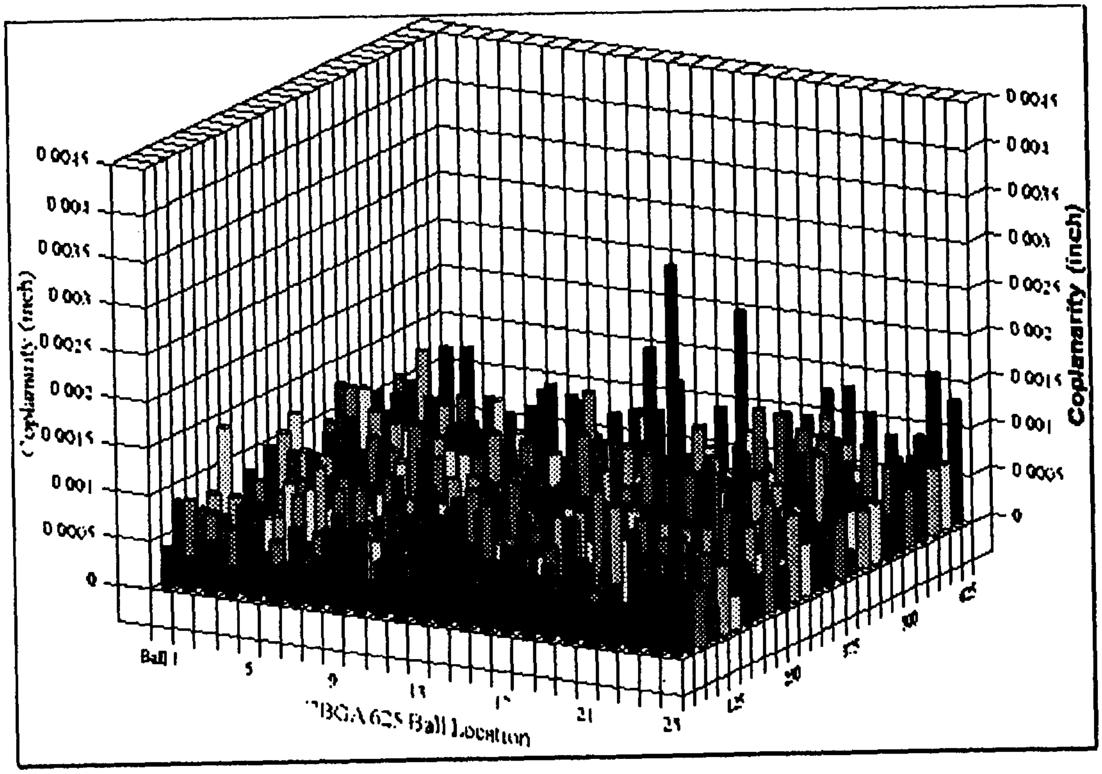


Figure 1 Package Dimensional Characteristics of Ceramic BGA with 625 I/Os

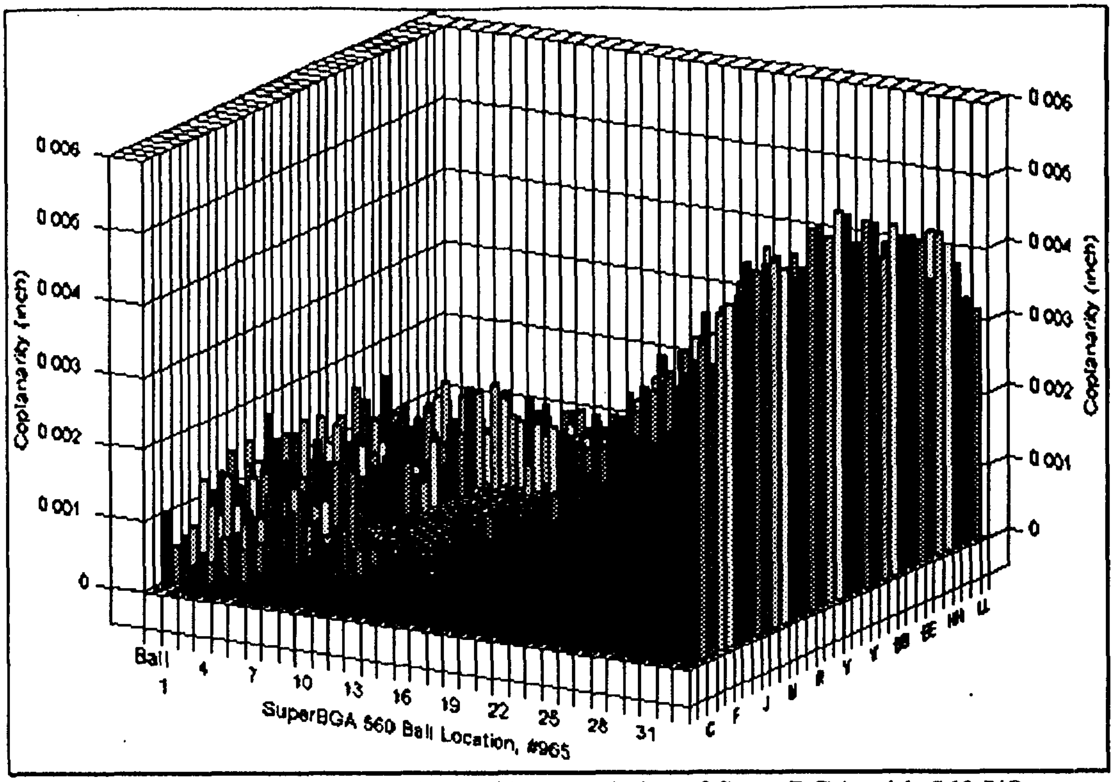


Figure 2 Package Dimensional Characteristics of SuperBGA with 560 I/Os

Package coplanarity is defined as the distance between the highest solder ball (lead for QFP) and the lowest solder ball. In the 3D laser technique, planarity of individual balls are calculated relative to the seating plane formed from the three tallest balls. Table 1 summarizes planarity results. Solder ball planarities were significantly higher for plastic than for ceramic packages and note that they, irrespective of package type, decreased as the size decreased.

Table 1. Planarities of CBGAs and PBGAs

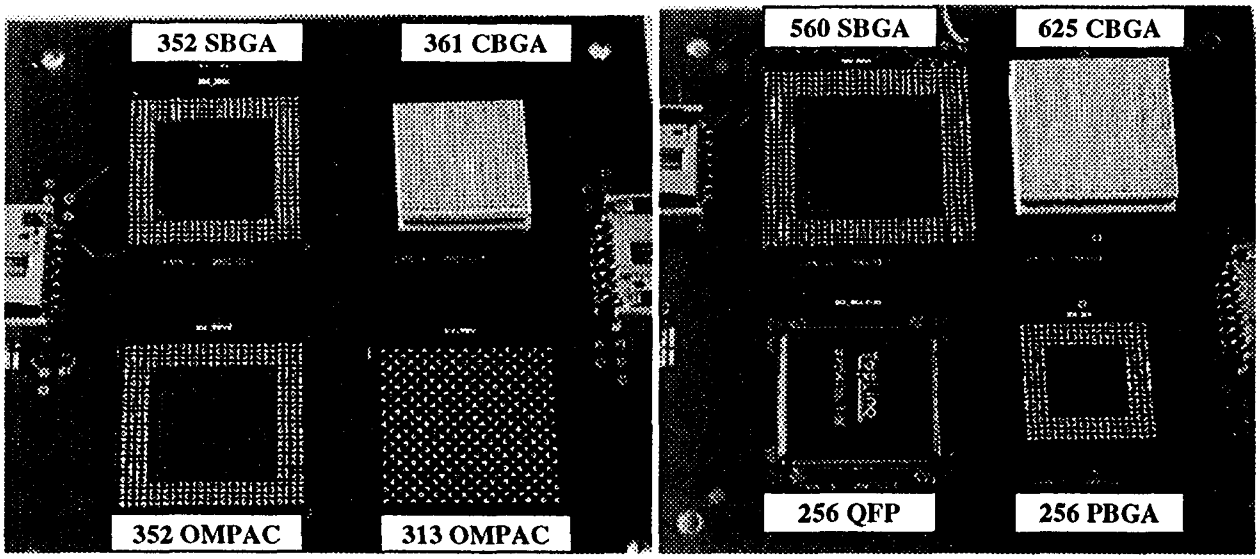
Package Type	Coplanarity Range (inch)
CBGA 625	0.0015-0.002 for 104 0.0030-0.004 for 4
CBGA 361	0.0012-0.0022 for 102
560 SuperBGA	0.002-0.004 for 72 0.004-0.006 for 45 0.006-0.0077 for 4
352 SuperBGA	0.0014-0.0037 for 145 0.0048,0.0058,0.0065,0.0091
352 OMPAC	0.0024-0.0057 for 128
313 OMPAC	0.0022-0.0052 for 140
256 OMPAC	0.0021-0.0047 for 140

Test Vehicle Assembling

Full assembly was implemented after process optimization from the trial test. The following procedures were followed:

- PWBs were baked at 125°C for four hours prior to screen printing.
- Two types of solder pastes were used, an RMA and a water soluble one.
- Pastes were screen printed and the heights were measured by laser profilometer. Three levels of paste were included in the evaluation: Standard, high, and low. Stencils were stepped to 50% to accommodate assembling ceramic, plastic, and fine pitch QFP packages in the Type 2 test vehicle.
- A 10 zone convection oven was used for reflowing.
- The first assembled Test Vehicle (TV) using an RMA reflow process was visually inspected and X-rayed to check solder joint quality.
- All assemblies were X-rayed
- Interchangeability of reflow profile for RMA and Water Soluble (WS) solder pastes was examined. One TV with water soluble solder paste was reflowed using the RMA reflow profile. These solder joints showed much higher void content than expected as well as signs of flux residues.
- For water soluble paste, a new reflow profile was developed based on the manufacturer's recommendation. This reflow process was used for the remaining test vehicles.

Two test vehicles were assembled (see Figure 3):
- Type 1, ceramic and plastic BGA packages with nearly 300 I/Os
- Type 2, ceramic and plastic BGA packages with nearly 600 I/Os. Also utilized were a 256 leaded and a 256 plastic BGA package for evaluating and directly comparing manufacturing robustness and reliability.
- Assemblies with water soluble flux were cleaned using an Electrovert H500. Those with RMAs were cleaned used Isopropyl Alcohol (IPA) and a 5% saponifier.
- All fine pitch QFPs had to be reworked for bridges.



a) Type 1 BGA Configuration and I/Os **b) Type 2 BGA Configuration and I/Os**

Figure 3 Test Vehicles with Unassembled Parts Topping Assembled Ones

BGA THERMAL CYCLING

Two significantly different thermal cycle profiles were used at two facilities. The cycle A condition ranged -30 to 100°C and had increase/decrease heating rate of 2°C/min. and dwell of about 20 minutes at the high temperature to assure near complete creeping. The duration of each cycle was 82 minutes.

The cycle B condition ranged -55 to 125°C. It could be considered a thermal shock since it used a three regions chamber: hot, ambient, and cold. Heating and cooling rates were nonlinear and varied between 10 to 15 °C/min. with dwells at extreme temperatures of about 20 minutes. The total cycle lasted approximately 68 minutes. BGA test vehicles were continuously monitored through a LabView system at both facilities.

The criteria for an open solder joint specified in IPC-SM-785, Sect. 6.0, were used as guidelines to interpret electrical interruptions. Generally once the first interruption was observed, there were many additional interruptions within 10% of the cycle life. In several instances, a few non-consecutive early interruptions were not followed by additional interruptions until significantly later stages of cycling. This was found more with plastic packages.

In Figure 4, the total number of electrical interruptions (daisy chain opens) are plotted vs. number of cycles for cycle B condition. For ceramic BGAs, the rate of interruptions (slope) were approximately constant of the same values. This was not the case for the plastic BGAs. For a PBGA with 313 I/Os, the first interruption was at 913 cycles with no additional interruptions until about 3,000 cycles. Further erratic interruptions were observed between 3,000 and 3,700 cycles, followed with linear interruptions having approximately the same slope as the CBGAs. Another PBGA showed the first interruption at 3130 cycles and become open at about 3,300 cycles.

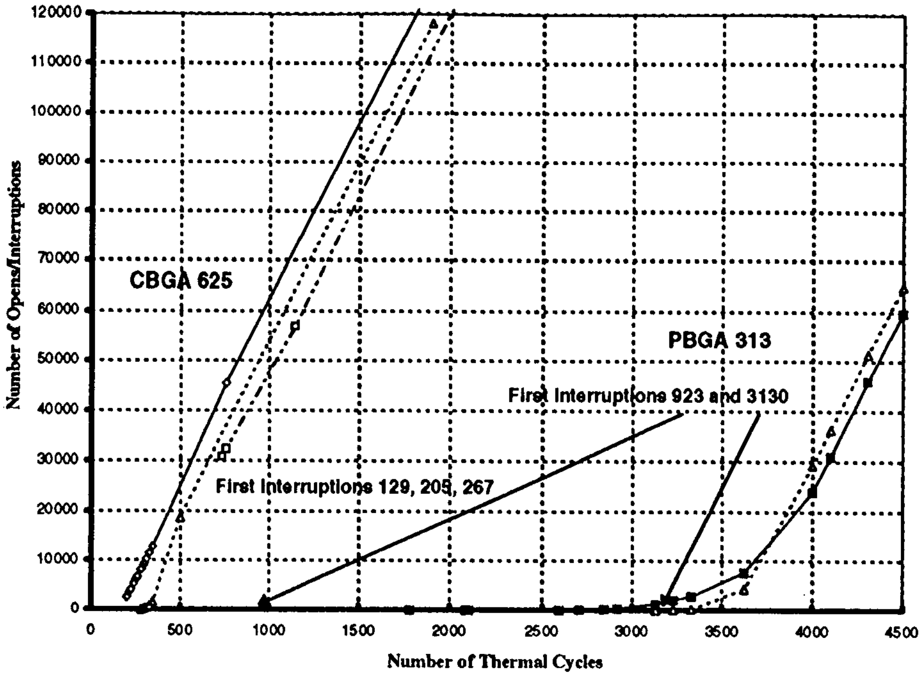


Figure 4 Number of Electrical Interruptions Detected with Thermal Cycles (-55°C<>125°C, B) for Ceramic and Plastic BGAs

Damage Monitoring

For conventional SMT solder joints, the pass/fail criteria for high reliability applications relies on visual inspection at 10x to 50x magnifications. For BGA, only edge balls, those not blocked by other components, were visually inspected. A series of single assemblies cut from the test vehicles were used for both visual and SEM inspection to better define visual criteria for acceptance of solder joints as well as to monitor damage progress under different cycling environments.

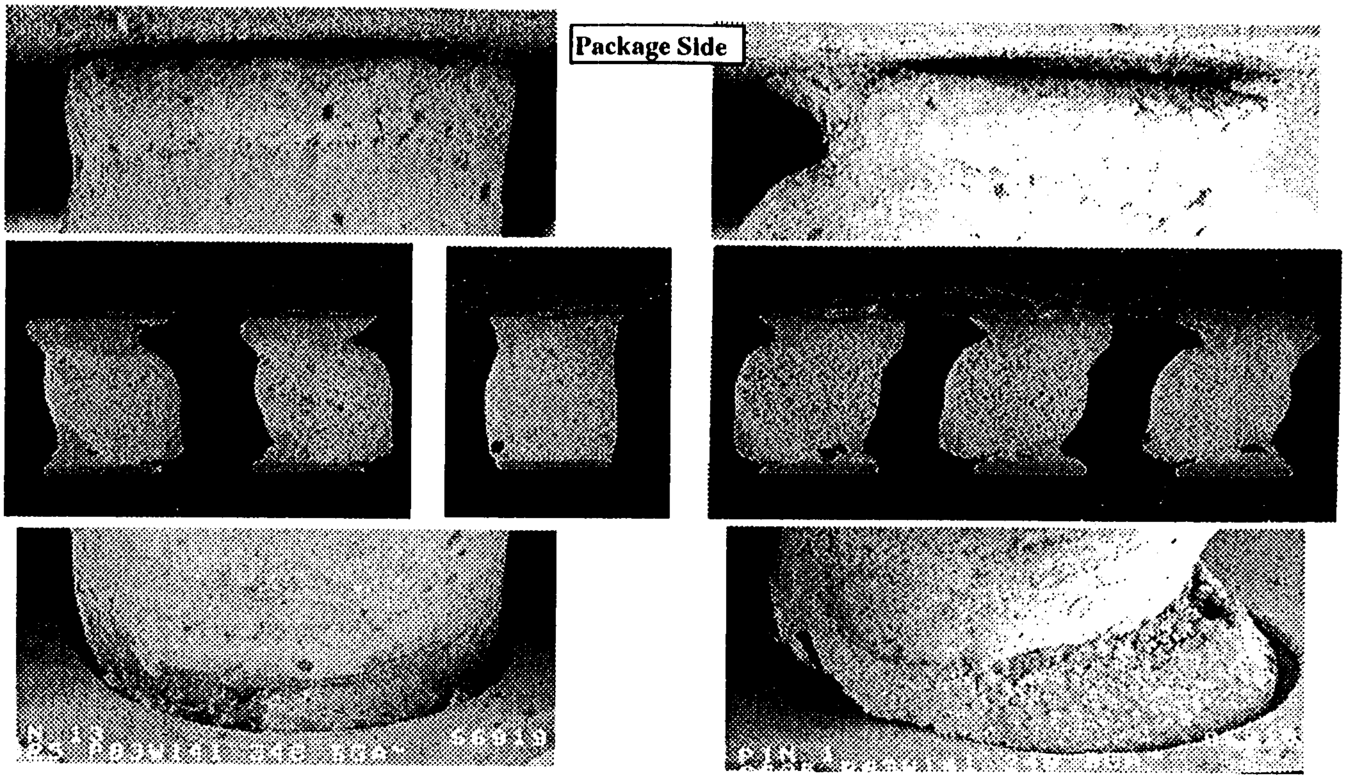


Figure 5 SEM and Cross-section photos for CBGA 625 after 348 cycles (-30°C to 100°C)

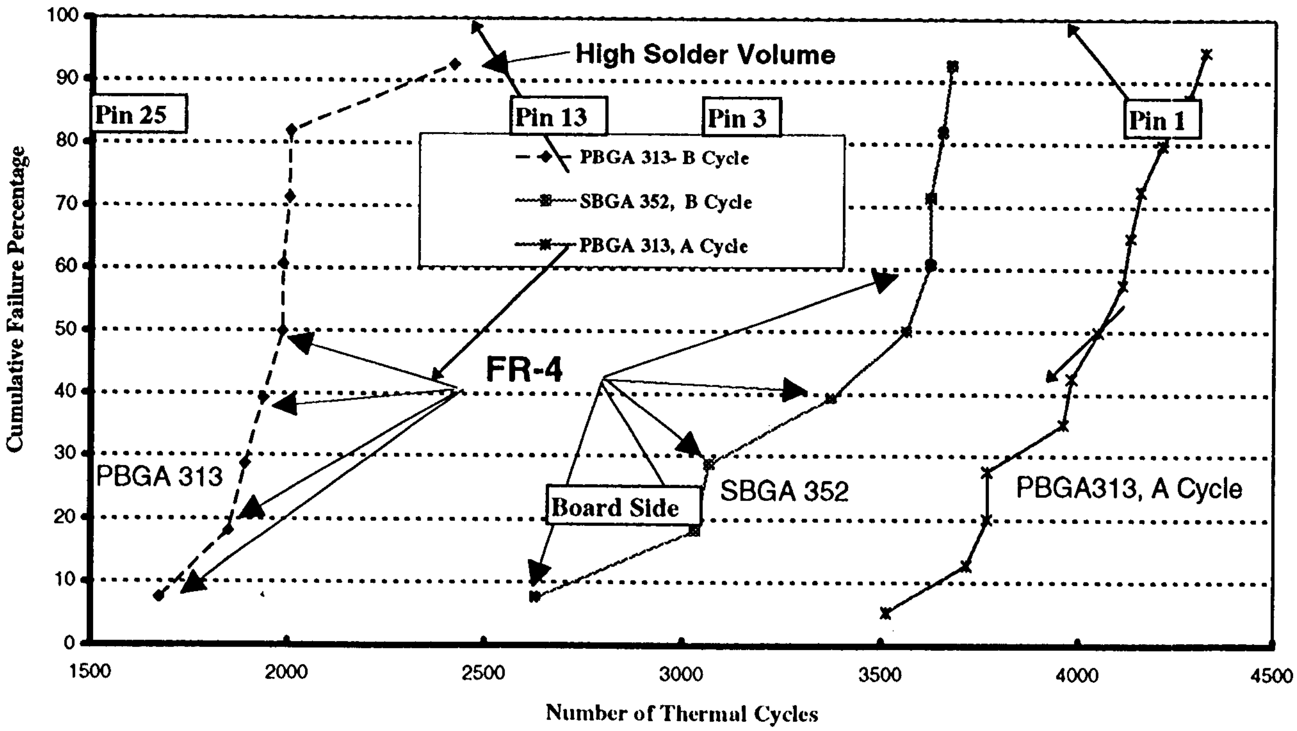


Figure 6 Cycles to Failure for PBGA 313 & SBGA 352 Assemblies (-55°C<>125°C, B) and PBGA 313(-30°C<>100°C, A)

Figure 5 shows a representative SEM and cross-sectional micrographs for a CBGA 625 after 348 cycles of A conditions. Cross-section photos are for the perimeter balls, two corners and a center ball. SEM photos for package and board sides of a corner (maximum Distance to Neutral Point (DNP)) and the edge center ball are included.

For the B cycles, ceramic packages failed at the package interface with signs of significant creeping and solder grain growth[3]. The board side solder creeping and cracking were much milder than package side.

Thermal Cycling Results

Figure 6 shows cycles to first failure for PBGA 313 and SBGA 352 subjected to B cycling for assemblies on polyimide and FR-4 PWBs. The most current PBGA 313 assemblies that failed under cycle A conditions are also included in the plots for comparison. These assemblies include those reflowed with low, standard, and high solder paste levels.

The cycles to failure were ranked from low to high and failure distribution percentiles were approximated using median plotting position, $F_i = (i-0.3)/(n+0.4)$. Weibull parameters will be generated when all failure data are gathered.

CONCLUSIONS

BGA Packages and Assembly Reliability

- Planarity levels are dependent on package type, but irrespective of the type decreased as the size decreased.
- Ceramic packages showed lower warpage and were more coplanar than their PBGA counterparts. Numerous ceramic packages had tilted solder balls.
- Solder ball planarities were significantly higher for plastic than for ceramic packages. A few PBGAs showed unexpectedly higher values above their norm distribution. PBGAs, however, are more robust and the large planarity values might not be as detrimental to their solder joint reliability as for ceramics. Some planarity differences among the PBGA balls could be accommodated by their collapse during the reflow process. This is not the case for CBGAs where high melt solder balls would remain intact during reflow. The solder ball diameter controls the stand-off height which is a key factor in solder joint reliability.
- 3D laser scanning is an excellent method for characterization of solder ball planarity and package dimension measurements, but possibly not for solder ball diameter evaluation.

BGA Assembly Reliability

- The BGA assembly void levels were the same as those generally observed by industry. As expected, BGAs were robust in assembly compared to the 256 fine pitch, 0.4 mm QFPs. All QFPs showed bridging to some degree and had to be reworked.
- RMA and water soluble reflow profiles evaluated in this study were significantly different and they were optimized separately for the applications. Large number of rather smaller and sporadic voids were generated when an RMA reflow profile for a water soluble solder paste was used.
- As expected, ceramic packages failed much earlier than their plastic counterparts because of their much larger CTE mismatch on FR-4/Polyimide boards. Cycles to electrical failure depended on many parameters including cycling temperature range and package size (I/O).
- Ceramic packages with 625 I/Os were first to show signs of failure among the ceramic (CBGA 361) and plastic packages (SBGA 560, SBGA 352, OMPAC 352, and PBGA 256) when cycled to different temperature ranges.
- Joint failure mechanisms for assemblies exposed to two cycling ranges at two facilities were different. Ceramic assemblies cycled in the range of -30°C to 100°C showed cracking initially at both interconnections with final separation generally from the board side through the eutectic solder. The board side joints showed signs of pin hole formation prior to cracking and complete joint failure. This failure mechanism is similar to those reported in literature for 0°C to 100°C thermal cycles.
- Ceramic and plastic BGAs showed different failure mechanisms as evidenced from the total number of electrical interruptions with increasing cycles. For CBGAs, the first electrical interruption (open) was followed by consecutive additional interruptions. This was not the case for PBGAs where the first interruption was not followed by additional interruptions until much a higher number of cycles.

- The PBGAs with 313 I/O, depopulated full arrays, were first among the PBGAs to fail within both cycling ranges. It has been well established that this configuration, with solder balls under the die, is not optimum from a reliability point of view.
- Solder volume is generally considered to have negligible effect on plastic package assembly reliability. One PBGA 313 package that was assembled with a high solder paste volume under cycle B exposure showed the highest number of cycles to failure. This will be assessed when data for cycle A become available.
- The 352 SBGA with no solder balls under the die showed much higher cycles to failure than the PBGA 313, depopulated full array, when subjected to cycle B conditions.
- For cycle B conditions, plastic package assemblies (PBGA 313 and SBGA 352 on polyimide) generally failed at a higher number of cycles than those on FR-4.

References

[1] Ghaffarian, R. "Area Array Technology Evaluation for Space and Military Applications", *The 1996 International Flip Chip, Ball Grid Array, TAB and Advanced Packaging Symposium Proceedings,* February. 13-16, 1996.

[2] Ghaffarian, R. "CBGA/PBGA Package Planarity and Assembly Reliability", *The 1997 International Flip Chip, Ball Grid Array, TAB and Advanced Packaging Symposium Proceedings,* February. 17-19, 1997.

[3] Ghaffarian, R., Kim, N. P."Ball Grid Reliability Assessment for Aerospace Applications," *30th International Symposium on Microelectronics,* October. 12-16, 1997

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